Suitability of polymer mortars for repairing seismic damaged ancient masonry pagodas

Shengcai Li*, Can Wang, Yuewen Gao

School of Architectural Science and Civil Engineering, Yangzhou University, Yangzhou, China

Received 12 August 2014, www.cmnt.lv

Abstract

To assess the properties of polymer mortars for seismic damaged ancient masonry to be bonded and strengthened by steel strips, such as fibre-reinforced mortar and acrylic-emulsion cement mortar, it is vital to conserve the cultural relics of ancient masonry pagodas. In this paper, the compressive strength, split strength, carbonation, and weatherability of the polymer mortars were obtained from mechanical tests and freeze-thaw cycling tests. By comparing corresponding parameters and analyzing internal microscopic structures from electron microscopy scanning photos, the reliability of the repair scheme on physico-mechanical properties of the polymer mortars has been evaluated, and some suggestions have been proposed.

Keywords: Seismic damaged ancient pagoda, Polymer bonding mortar, Physico-mechanical properties, Weatherability, Microstructure

1 Research aims

FIGURE 1 Longhu ancient pagoda (a) Seismic damage view; (b) strengthening steel strips; (c) embedded steel bar; and (d) photo after being repaired.

Due to seismic vulnerability, ancient masonry structures were regularly repaired and reinforced with mortars, steel, and other materials. The performance of mortars of different ingredients is not the same, which might lead to reliability problems in certain situations. The research presented in this paper aims at determining the suitability of polymer mortars for repairing seismic damaged ancient masonry pagodas by comparing physico-mechanical properties, weatherability, porosity, and the microstructure of polymer mortars.

2 Introduction

Some ancient masonry pagodas which were destroyed by the Wenchuan Earthquake in 2008 have been repaired by mortar and steel strips [1]. Fig. 1 shows the seismic damage of an ancient pagoda in Sichuan, China, and the schematic diagram of reinforcements and repairs. Mortars play important roles in the repair scheme, such as bonding, plastering, screeding, and decorating. Instead of traditional mortar, polypropylene fibre reinforced mortar, and epoxy resin mortar were developed and used to meet corresponding requirements in repair schemes.

Additives, such as swelling agents, anti-corrosion admixtures, and water-reducing agents were added into mortars to improve the mortars' performance, so that the repaired masonry structure was well protected. The existent research results show that additives in mortars play unique roles in improving the physico-mechanical properties of mortars [2 - 6]. As additives in mortar, styrene butadiene rubber latex could increase the tensile and compressive strength of mortar. Cellulose ether could also increase the bonding strength of mortar. Moreover, epoxy and acrylic emulsions could cause mortar to have superior strength properties and better resistance to the penetration of chloride ions and carbon dioxide. Acrylic and butyl acrylate could also improve the durability of mortar. In addition, ethylene vinyl acetate copolymer emulsion could improve the performance of carbonation resistance of mortar. Workability of mortar could also be improved by additives [7]. Furthermore, SBR emulsions polymerisation could improve the workability of mortar. Additives have different composite mechanisms and produce microstructures which make mortars present different properties [8]. Polymer-cement mortars for repairing ancient masonries should have special mechanical properties so that the repair quality could be ensured [9, 10].

However, it is hard to discover a mortar with optimal ingredients that is suitable to bond steel strips and repair ancient masonry pagodas. In this paper, mortar specimens

* ***Corresponding author*** e-mail: li_shcai@126.com / lisc@yzu.edu.cn

with different ingredients were designed and tested according to the professionalism of heritage conservation, in order to determine the suitability of polymer mortar to repair seismic damaged ancient masonry pagodas.

3 Materials and methods

3.1 RAW MATERIAL

According to the repair cases in Sichuan, the specimens for testing were made from P.O 42.5 cement, special acrylic-emulsion matched with cement mortar, polypropylene fibre, UEA-IV swelling agent, K-16 anti-corrosion admixture, JH-202 air entraining water-reducer, and epoxy resin. All of the raw material is made in China and meets the requirements of corresponding quality specifications.

3.2TEST SCHEME AND SPECIMEN

In order to probe the physico-mechanical properties and workability that are related to repairing quality, mechanical tests, freeze-thaw cycling tests, and electron microscopy scanning on the specimens should be conducted so that corresponding parameters which are used to identify the mortars with optimal ingredients for certain objectives could be extracted from the test data.

A YE-2000 universal testing machine is utilized to conduct a test of compressive strength. A WE-300 universal testing machine is used to carry out a split test of tensile strength. A CCB-70A carbonation resisting test chamber is employed to conduct a test of carbonation depth. A CLD anti-freezing test chamber is used to conduct a frozen and thaw cycle test. A SCD500 ion sputtering coating machine and XL-30ESEM scanning electron microscope are utilized to test the porosity and microstructure of the mortars.

The mortar specimens were classified into four categories, which were numbered from I to IV according to their ingredients. Moreover, each category of mortar consists of four groups of specimens, which were numbered from A to D, according to the proportion of additives, such as polypropylene fibre, acrylic emulsions, UEA swelling agents, air-entraining water reducers, anti-corrosion admixtures, and epoxy resin. The weight ratio of cement-sand in group I is 1:5.27. Each specimen in this paper has the same ratio of cement-sand. The differences between the specimens are the additive ingredients and corresponding proportions, except for cement, water, and sand. The details of the additives in each specimen are as follows:

Group I-A: no additive; Group I-B: 1% air-entraining water-reducer; Group I-C: 2% anti-corrosion admixture; Group I-D: epoxy resin.

Group II-A: 0.09% polypropylene fibre; Group II-B: 0.1% polypropylene fibre; Group II-C: 0.11% polypropylene fibre, Group II-D: 0.12% polypropylene fibres.

Group III-A: 24% acrylic emulsions; Group III-B: 26% acrylic emulsions; Group III-C: 28% acrylic emulsions; Group III-D: 30% acrylic emulsions.

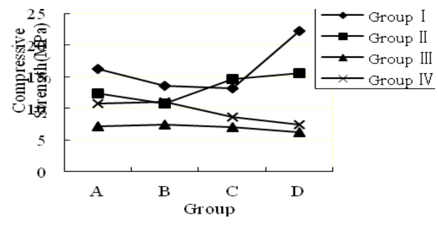
Group IV-A: 8% UEA swelling agent; Group IV-B: 10% UEA swelling agent; Group IV-C: 12% UEA swelling agent; Group IV-D: 14% UEA swelling agent.

The percentage of an additive in a specimen is the ratio of the weights of the additive to the cement in a specimen. According to the ratio of water-cement, the specimens are divided into two groups. The ratio of water-cement in one group is 0.5, and the other one is 0.8. There are nine pieces of specimens in each group for the strength test and carbonization test. The size of each specimen is 100 mm ×100 mm ×100 mm. Furthermore, there are three pieces of specimens in each group for the freeze-thaw cycle test. The size of each specimen is 40mm × 40 mm ×160 mm. Specimens were cured over a period of 28 days in a standard condition, with a temperature of 20± 2 oC and relative humidity of 90%.

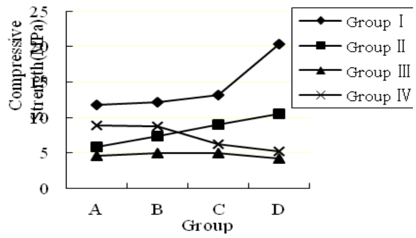
4 Result and discussion on mechanical properties

4.1 COMPRESSIVE STRENGTH

The test data on the compressive strength of the specimens are shown in Fig. 2. By comparing the strength values from the specimens of different groups, some relationships could be determined. There is a slight difference between group I-A, I-B, and I-C. This means that a certain amount of the additives of air-entraining water reducer and anti-corrosion admixture could cause a change of the compressive strength of ordinary mortar. However, the epoxy resin could make a large increase of the compressive strength of ordinary mortar; this phenomenon has been proven [11]. Additionally, the epoxy resin could increase the internal compactness of cement mortar after hardening. The polypropylene fibre in the specimens of group II could reinforce mortar. Furthermore, the compressive strength of the specimens in group II could be improved with the increase of the proportion of polypropylene fibre present in a certain range. However, if the polypropylene fibres have not been mixed and scattered evenly into the mortar, the compressive strength would decrease. There is a slight influence on the compressive strength from acrylic emulsions in the specimens of group III. The optimal percentage of acrylic emulsions in the specimens is 28%. Moreover, UEA swelling agent will decrease the compressive strength in the specimens of group IV. The optimal percentage of UEA swelling agent is 10% in the test.



(a) W/C=0.5



(b) W/C=0.8

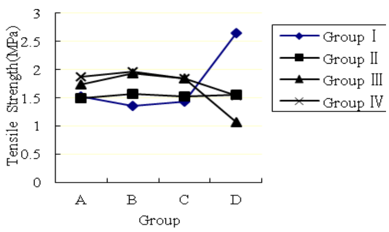
FIGURE 2 Compressive strength of the specimens at 28 days

Generally, the polypropylene fibre, acrylic emulsions, and UEA swelling agent in cement mortar will cause a decrease of compressive strength.

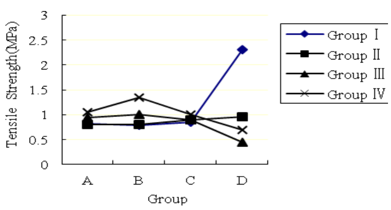
FIGURE 4 CCB-70A carbonation-resisting test chamber.

4.2 TENSILE STRENGTH

The test data on the tensile strength of the specimens are shown in Fig. 3. According to the test data, the additives, such as epoxy resin, polypropylene fibres, acrylic emulsions, and UEA swelling agents could improve tensile performance. Epoxy resin could also efficiently increase the bond strength between sands; thus, the tensile strength of group I-D specimen is significantly higher than other groups. Because of the viscosity, acrylic emulsions could improve the mortar's bond performance. The optimal proportion of added acrylic emulsions is 26% of the cement's weight in the specimen. The adsorption of ettringite crystal from the hydration of UEA swelling agent plays an important role in increasing the bond strength of cement mortar. The optimal proportion of added swelling agent is 10% of the cement's weight in the specimen. Because of smooth surface, low surface energy, the lack of any active group in its molecular chains, and surface hydrophobic nature, polypropylene fibres were weakly embedded in cement mortar. Therefore, the tensile strength could be increased slightly.



(a) W/C=0.5



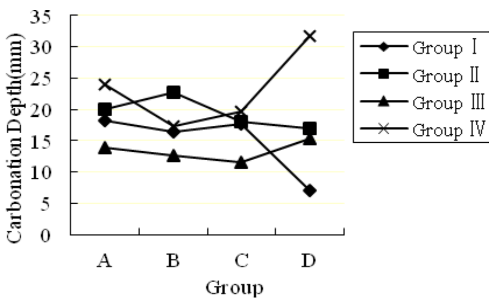
(b) W/C=0.8

FIGURE 3 Tensile strength of the specimens at 28 days

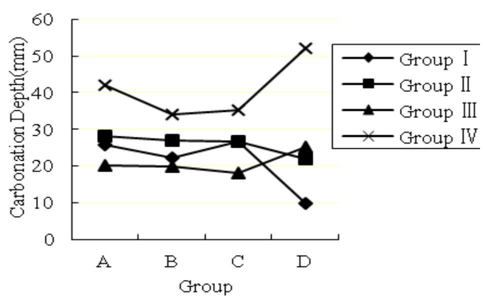
5 Result and discussion on weatherability

5.1 CARBONATION RESISTANCE

The test device for measuring carbonation resistance is shown in Fig. 4. Carbonation resistance of a mortar could be measured by the carbonation depth of the corresponding specimens. The test data on carbonation depth are shown in Fig. 5 According to the test data shown in Fig. 5a and Fig. 5b, the carbonation depth is different for the same mortar under the condition of different ratios of water-cement. If the water-cement ratio is smaller, the carbonation depth is also smaller [12]. This means that the density of the mortar is greater, and its carbonation resistance is higher. For the specimens of group I-B obtained by adding the air entraining water reducer, the carbonation depth is smaller than that of group I-A without the additive of air entraining water reducer. In an interior environment, the addition of epoxy resin into the specimens of group I-D significantly improved carbonation resistance. The test data on the specimens in group II show that polypropylene fibre reduces the carbonation resistance of cement mortar. This phenomenon might be caused by the internal structure defects that are produced by polypropylene fibre and easily permeated by CO2 [13]. The test data on the specimens in group III demonstrate that acrylic emulsions could significantly improve carbonation resistance of cement mortar. Furthermore, when the added amount of acrylic emulsions is 28% of the weight of cement, the carbonation resistance of an acrylic mortar could be the best. The test result of the specimens in group IV shows that the additive of UEA swelling agent does not play a positive role in the carbonation resistance of a mortar. In fact, UEA swelling agent might produce more carbonized material and interrupt the process of cement hydration.



(a) W/C=0.5



(b) W/C=0.8

FIGURE 5 Carbonation depth of the specimens at 28 days

5.2 FROZEN AND THAW PROPERTIES

The test device for measuring the number of frozen and thaw cycles is shown in Fig. 6. The number of frozen and thaw cycles of each specimen is 200. The mass of each specimen is weighed after every 25 cycles of frozen and thaw cycle. If the mass loss of a specimen was 5%, the specimen was distinguished as frost-damaged. Additionally, if two specimens in a group with three specimens were damaged, it could be judged that the group's specimens were frost-damaged. The damaged specimens are shown in Fig. 7. The test data on frozen and thaw cycles are shown in Table 1 and Table 2.

The test data proves that air entraining water-reducer and epoxy resin could greatly increase resisting performance of the freezing-thawing. Moreover, polypropylene fibres could reinforce cement mortar and provide greater toughness for cement mortar, so that the kind of fibre mortar could improve the ability of resistance to deformation and cracking due to temperature differences. Furthermore, the effect could be most efficient when the added amount of polypropylene fibres is 0.12kg/m3. Acrylic emulsions could also increase freezing-thawing resisting ability according to test data on acrylic emulsions cement mortar in group III. If the added amount of acrylic emulsions is 28% - 30% of the weight of the cement in the composite mortar, the freezing-thawing resisting ability is the best. Additionally, the freezing-thawing resisting ability of specimens obtained by adding UEA swelling agent is fairly weak. This is probably due to the swelling effect from the ettringite crystal, which is the product of hydration of UEA swelling agent. The swelling effect leads to rapid change of the internal stress in a mortar.

FIGURE 6 CLD anti-freezing test chamber

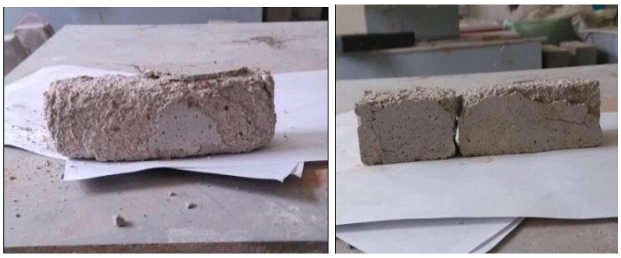


FIGURE 7 Damaged specimens of frozen and thaw cycle test

TABLE 1 Freezing-thawing test on the specimens with W/C=0.5

Group	A	B	C	D
Group I	1.60%	0.13%	3.74%	0.07%
Group II	0.45%	0.22%	0.19%	0.16%
Group III	1.42%	0.38%	0.20%	175
Group IV	75▲	100▲	2.68%	2.39%

TABLE 2 Freezing-thawing test on the specimens with W/C=0.8

Group	A	B	C	D
Group I	3.06%	0.24%	125▲	0.15%
Group II	0.91%	2.10%	0.56%	0.25%
Group III	0.55%	0.67%	0.54%	0.94%
Group IV	75▲	75	75	100▲

Note 1. The percentage of mass loss is expressed in %. If there is no percentage sign in a table cell, it means that the specimen is damaged. In this case, the value in the corresponding table cell indicates the number of frozen and thaw cycles.

Note 2. The sign "▲" means that all the specimens in the group were damaged.

6 Result and discussion on microstructure

6.1 POROSITY

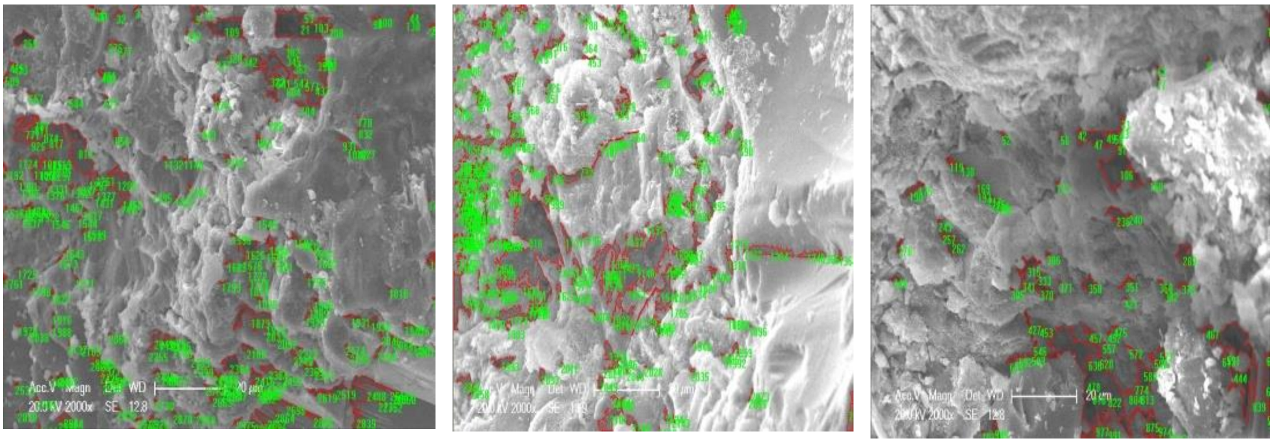
The test devices for microstructure are shown in Fig. 8.

(a) Scanning electron microscope

(b) SCD500 ion sputtering coating machine

FIGURE 8 Test device for microstructure

The slices for the observation and analysis with high performance scanning electron microscope are cut by a special tool from different parts of the specimens, which were cured in the same condition as for the above specimens and were kept in a normal interior climate environment for 48 h. The size of each slice is 3mm ×3mm ×3 mm. The observations of topography were conducted with a scanning electron microscope, and the topographies were obtained and magnified 2000 times. The porosity analysis was implemented with the Image Pro Plus software. Fig. 9 shows the images of three slices from one of the specimens in group I-A, whose ratio of water-cement is equal to 0.5.

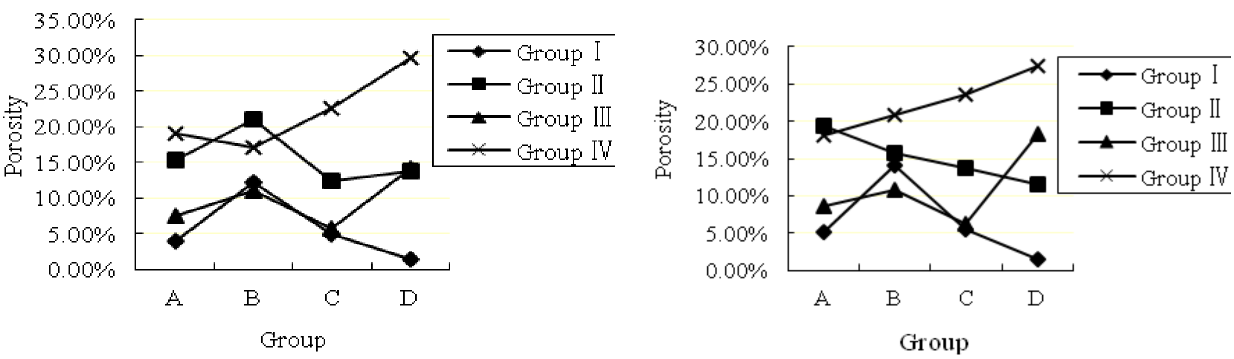


(a) The top part of a specimen (b) The middle part of a specimen (c) The bottom part of a specimen

FIGURE 9 Porosity analysis of the specimen in group I-A (the red color in the picture represents pore space, and the green color represents the number of pores)

6.2 THE QUALITATIVE ANALYSIS OF MICROSTRUCTURE

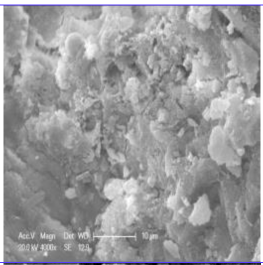
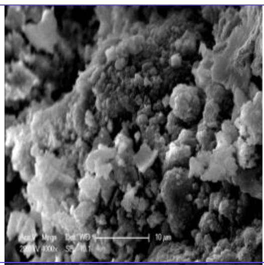
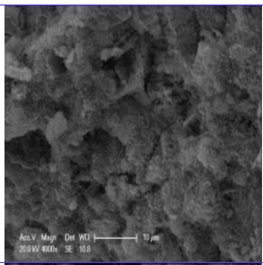
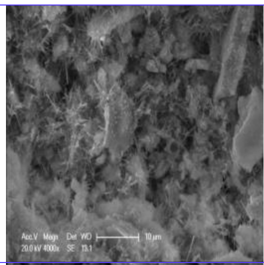
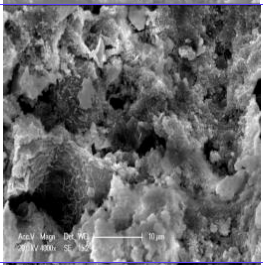
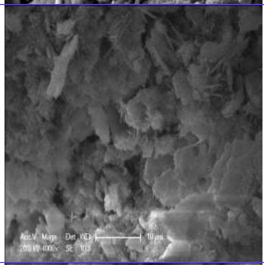
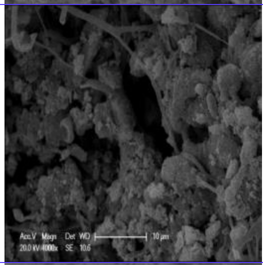
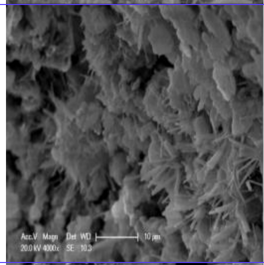
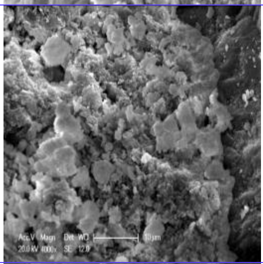
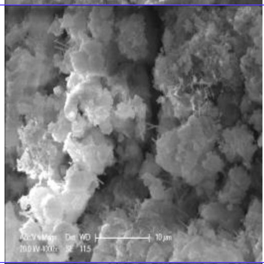
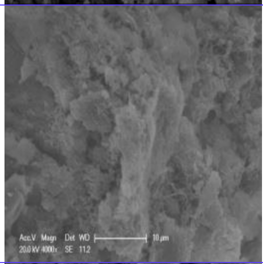
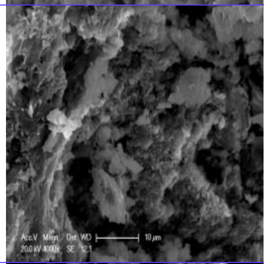
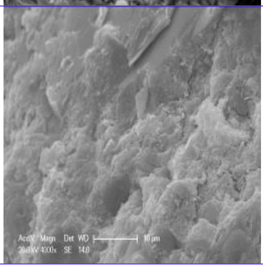
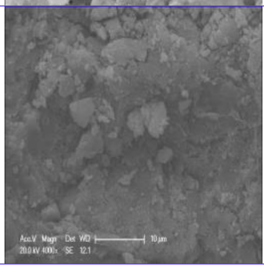
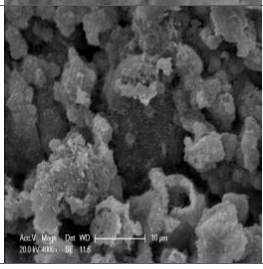
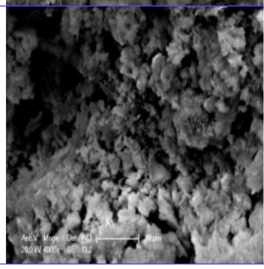
The porosity of the specimen in each group is shown in Fig. 10. According to the quantitative analysis, the porosity of the epoxy mortar in group I-D is significantly lower than that of other specimens. The specimens in group I-B obtained by adding air-entraining water-reducer have more pore space than those of pure cement. The porosity of the specimens obtained by adding polypropylene fibre would decrease by increasing the added amount of polypropylene fibre. The porosity of the specimens in group III obtained by adding acrylic emulsions is higher than that of plain cement mortar with the same water-cement ratio. The porosity of the specimens in group IV obtained by adding UEA swelling agent is fairly high. The microscopic image of the specimens is shown in Table 3.



(a) W/C=0.5 (b) W/C=0.8

FIGURE 1 Porosity analysis of the microstructure in specimens

TABLE 3 Microscopic image of the specimens

Groups	I	II	III	IV
A				
B				
C				
D				

Based on the above microscopic image, the composite mechanisms and microstructures of mortar with different additives could be analysed. Air-entraining water-reducer could produce uniformly distributed porosity of a mortar and improve mortars' freezing-thawing resisting performance. Insoluble polymer from epoxy resin improves the mortar in terms of mechanical properties and durability. Fibres in mortar produce more defective porosity, which could reduce the performance of carbonization resisting and freeze-thaw resisting. When moisture in acrylic emulsions is evaporated, micro-channels are formed and carbonation resistance and freeze resistance of a mortar will be decreased. UEA swelling agent will produce more pore defects in mortar.

7 Conclusions

According to the above test data, analyses and discussion, it is apparent that every mortar has its own properties. The choice of a mortar should be carefully managed according to the multiple factors which might influence the quality of repairing a masonry pagoda. Some conclusions could be drawn as follows:

(1) The mortar with a lower ratio of water-cement and with the addition of air-entraining water-reducer or acrylic emulsions could have better durability than that of other category mortars. Thus, it could be applied as the covering layer.

(2) The epoxy resin mortar could have high mechanical and durability properties. It is suitable to bond steel strips with masonry structure.

(3) UEA swelling agent could produce compressive prestress in mortar. This could help to resist the tensile stress produced by temperature differences. However, its weatherability is fairly weak. It would be optimal if it was covered with high durability mortar.

(4) The anti-corrosion admixture seems to play only a slight role in a mortar. If there is not any corrosion ingredient in a mortar which could corrode the steel strips, it is better not to add anti-corrosion admixture into a mortar for repairing ancient masonry pagodas.

Acknowledgements

This paper is supported by the National Natural Science Foundation of China (Grant No. 51078323, 51211130119) and the Royal Society of International Exchanges (Grant No. IE111311).

References

[1] Can W and JianLi Y 2012 Applied Mechanics and Materials 166-169, 2143-50
[2] Bureau L, Alliche A and Pilvin P 2001 Mater. Sci. Eng. A 308, 233-40
[3] Jenni A, Holzer L, Zurbriggen R and Herwegh M 2005 Cem Concr Res 35, 35-50
[4] Aggarwal L K, Thapliyal P C and Karade S R 2007 Construction and Building Materials 21, 379–83
[5] Hyung, Won Gil 2009 Polymer-Korea 33(4), 342-6
[6] Dazhi L, Hongqiang C and Linhua J 2010 Advances in Science and Technology of Water Resources. 30(6), 39-42.
[7] Ukrainczyk N and Rogina A 2013 Cem. Concr. Compos. 41, 16-23.
[8] Etsuo S and Jun S 1995 Cem. Concr. Res. 25(1) 127–35
[9] Anagnostopoulos C A and Anagnostopoulos A C 2002 Construction and Building Materials 16(7), 379-84.
[10] Anagnostopoulos C A 2007 Construction and Building Materials 21, 252–7
[11] Rahman M 2012 Iran. Polym. J. 21(9) 621-9
[12] Vladimír Ž 2009 Construction and Building Materials 23(12) 3579–82
[13] Qi C Weiss J and Olek J 2003 Mater. Struct. 36(260), 386-95.

Authors

Shengcai Li, 21 Dec 1965, Jiangsu, China

Current position, grades: Associate professor
University studies: Civil Engineering in Hehai University, Architectural technology and science in Chongqing University, Architectural technology and science in Tongji University
Scientific interest: Conservation Technologies on Building Heritage
Publications: 31 papers + 2 books
Experience: Dr Li graduated from Tongji University with Ph D. He engages in teaching and academic research in Yangzhou University. He has worked in the field of Conservation Technologies on Building Heritage for 20 years. He has held two research projects from NSFC and has participated 6 research projects.

Can Wang, 11 Oct 1986, Jiangsu, China

Current position, grades: Engineer
University studies: Civil Engineering in Yangzhou University
Scientific interest: Conservation Technologies on Building Heritage
Publications: 1 papers
Experience: Mr. Zhao is good at numerical simulation on building structure with FEM. He has participated 2 research projects in the field of Conservation Technologies on Building Heritage.

Yuewen Gao, 12 Feb 1991, Jiangsu, China

Current position, grades: postgraduate
University studies: Civil Engineering in Yangzhou University
Scientific interest: Conservation Technologies on Building Heritage
Publications: 2 papers
Experience: Mr. Liu is good at numerical simulation on building structure with FEM. He has participated 2 research projects in the field of Conservation Technologies on Building Heritage.